PROGRESS REPORT FORM

1. PI: Joyce E. Penner, University of Michigan

2. Title of Research Grant: Cloud/Aerosol Parameterizations: Application and Improvement of General Circulation Models

3. Scientific Goal(s) of Research Grant:

One of the biggest uncertainties associated with climate models and climate forcing is the treatment of aerosols and their effects on clouds. The effect of aerosols on clouds can be divided into two components: The first indirect effect is the forcing associated with increases in droplet concentrations; the second indirect effect is the forcing associated with changes in liquid water path and lifetime of clouds. Both are highly uncertain. The goal of our project is to use data collected at the ARM site to evaluate both the first and second indirect effect. We will also use other data (specifically data collected by satellite) to validate our parameterization of indirect effects and to motivate and guide improvements in our parameterization.

4. Accomplishments

(1) Completed analysis of the first indirect effect in our climate model, including an analysis of the effects of including absorption by black carbon and submitted a paper.

(2) Organized and participated in a workshop for IPCC, which compared both direct and indirect forcing estimates from a number of different models. Aerosol concentrations and burdens were also examined. We are in the process of drafting several papers from this intercomparison.

(3) Completed analysis using our parameterization of the indirect effect in the Hamburg climate model. This model includes a treatment of both the first and second indirect effects. Two papers based on results from our parameterization were published.

(4) Examined the effect of changes in precipitation efficiency (i.e., the 2^{nd} indirect effect) caused by aerosols on the hydrological cycle within a climate model. A paper has been submitted to GRL.

(5) Analyzed whether the method commonly used to evaluate the 2^{nd} indirect effect is contaminated to a large extent by feedbacks, and showed that this method provides an adequate determination of global average forcing.

(6) Compared the correlation between modeled droplet concentrations and aerosol abundance with the correlation deduced from analysis of satellite (AVHRR) data. This analysis tends to support the notion that that the 2^{nd} indirect effect may be relatively small.

(7) Extended our analysis of data from the ARM site in Oklahoma to cover 10 different time periods. These data do not include a broad enough range in aerosol number concentration to provide a

conclusive test of the aerosol indirect effect. We will analyze data from the North Slope of Alaska once the satellite analysis becomes available.

5. Progress and accomplishments during last twelve months.

(1) Completed analysis of the first indirect effect in our climate model, including an analysis of the effects of including absorption by black carbon and submitted a paper.

We used our estimated aerosol concentrations and the University of Michigan/LLNL version of the CCM1 climate model to estimate the first indirect effect. The estimated forcing by sulfate, biomass, and fossil fuel carbon aerosols is -0.30 Wm^{-2}, 1.16 Wm^{-2}, and -0.52 Wm^{-2}. Failing to include absorption by black carbon aerosols within clouds makes only a small difference to the global average forcing, but can lead to a significant overestimate of forcing on a regional basis.

(2) Organized and participated in a workshop for IPCC which compared both direct and indirect forcing estimates from a number of different models. Aerosol concentrations and burdens were also examined. We are in the process of drafting several papers from this intercomparison.

We developed the experimental design and organized a workshop for aerosol model intercomparison for the IPCC. Eleven different modeling groups participated in the workshop. This was the first intercomparison that included organic and black carbon aerosols, sea salt aerosols, dust aerosols, as well as sulfate aerosols. We compared the modeled concentrations with available measurements and, for those models that included all components, we examined their ability to reproduce satellite-derived aerosol optical depth. Even though sulfate aerosols have been widely studied the total aerosol burden varies by more than a factor of 2 between the models. Larger discrepancies appear in other aerosol types. We used this analysis to derive uncertainties in aerosol forcing for the IPCC as well as estimates in future aerosol forcing. The latter analysis also included a preliminary analysis of forcing associated with changes in natural aerosol components that result from changes in climate.

(3) Completed analysis using our parameterization of the indirect effect in the Hamburg climate model. This model includes a treatment of both the first and second indirect effects. Two papers based on results from our parameterization were published.

We used our parameterization of aerosol/droplet interaction in the Hamburg climate model to estimate both the first and second indirect effect from both sulfate and carbon aerosols. The total forcing from these components ranged between -1.1 and -1.9 Wm^{-2}. Sulfate forcing was -0.4 Wm^{-2} while carbon aerosol forcing was -0.9 Wm^{-2} (this sums to slightly more than the combined forcing evaluated at -1.1 Wm^{-2}). The carbon particle forcing is smaller than that in the CCM1 model largely because this model assumes that carbon particles become hydrophilic with an e-folding lifetime of several days, while the

Grantour/CCM1 model assumes they are hydrophilic immediately (so there are a larger number of cloud forming particles in the Grantour/CCM1 model). Of the total forcing, almost half is associated with the 2nd indirect effect.

(4) Examined the effect of changes in precipitation efficiency caused by aerosols on the hydrological cycle within a climate model. A paper has been submitted to GRL.

The indirect effect of aerosols can alter the hydrologic cycle within a climate model. We examined this effect in a climate model that includes both the first and second indirect effects and found that the model predicted a significant southward shift of rainfall over the equatorial Pacific. This was mainly associated with the cooling of the Northern Hemisphere relative to the Southern Hemisphere.

(5) Analyzed whether the method commonly used to evaluate the 2nd indirect effect is contaminated to a large extent by feedbacks, and showed that this method provides an adequate determination of global average forcing.

The global average radiative forcing at the top of the troposphere is used as a first order estimate of the change in global average surface temperature ΔT_s of the climate system. It has historically been evaluated holding all components of the climate system constant (except for the stratospheric temperature) while perturbing only the component whose forcing is being evaluated. The second indirect effect cannot be evaluated this way, because changes to precipitation efficiency may suppress precipitation, thereby increasing cloud liquid water content and cloud lifetime, which may then result in an increase in the time averaged cloud amount. These components are intimately associated with changes in local temperature as well as cloud amount, so cannot be evaluated holding temperature fixed. We used a climate model to examine the validity of this method of evaluating forcing by examining a calculation of the forcing for the Twomey effect by both the “pure” technique and the approximate technique, and by examining the evaluation of forcing using the difference in cloud forcing as well as the difference in net radiative fluxes between the two model simulations. We confirmed that the common method used to evaluate forcing for the second indirect effect provides an adequate measure of global average forcing (to within 20%) and that the climate sensitivity remains roughly constant using this method of evaluating forcing.

(6) Compared the correlation between modeled droplet concentrations and aerosol abundance with the correlation deduced from analysis of satellite (AVHRR) data. This analysis tends to support the notion that the 2nd indirect effect may be relatively small.

The column aerosol particle number and low cloud microphysical parameters derived from AVHRR remote sensing were compared over ocean for four months in 1990. There is a positive correlation between the cloud optical thickness and aerosol number concentration, whereas the effective particle radius has a negative correlation with aerosol number. The column cloud particle number has a similar dependence on the column aerosol number as that proposed by Twomey (i.e., the first indirect effect). The cloud liquid water path (LWP), on the other hand, tends to be constant with no large dependence on aerosol number. This result contrasts with results from recent model simulations which imply that there is a strong positive feedback between LWP and aerosol number concentration that can more than double the forcing calculated if LWP is held constant. The correlation from this analysis was compared with those from our model predictions of droplet number concentration. Estimates for indirect forcing over oceans derived from the satellite data range from -0.7 to –1.7 Wm-2. These values are consistent with those from the model analysis. A paper describing these results has been submitted to Nature.

(7) Extended our analysis of data from the ARM site in Oklahoma to cover 10 different time periods. These data do not include a broad enough range in aerosol number concentration to provide a conclusive test of the aerosol indirect effect. We will analyze data from the North Slope of Alaska once the satellite analysis becomes available.

Data from the ARM site are being used to compare calculated reflected radiation from cloudy skies with that measured by satellite. The calculations take into account the effect of aerosols on cloud droplet number density and thus should enable us to validate parameterizations of the indirect effects of aerosols on cloud reflectivity. For adiabatic clouds, the indirect effect will be evident if there is a linear relationship between the quantity tau/H**5/3 and Nd**1/3 where tau is the optical depth of the cloud, H is the cloud height and N_d is the droplet number concentration predicted by the scheme. We have carefully screened the ARM data during those periods in which satellite analysis of reflected radiation is available to find periods of time when stratoform clouds are present and the cloud cover is nearly complete, when the atmosphere is well mixed below cloud base so that surface aerosol concentration data may be used in our parameterization at cloud base, when the clouds are nearly adiabatic, and when the evaluation of cloud base using the ceilometer data and the radiosonde data is similar. The analysis still shows a significant amount of scatter when plotted as tau/H**5/3 versus Nd**1/3. This is probably due to inaccuracies in the evaluation of cloud depth, H. We expect to carry out further analysis once the cloud radar data for H become available. In addition, the data available from the Oklahoma site do not cover a wide range of values of Nd. This range can be extended once the satellite data become available for the North Slope of Alaska.

6. As appropriate attach one or so electronic figures with paragraph discussions highlighting current research. (I have not included any figures - the radiative forcing predicted by our model is available as a figure from Cathy Chuang's report).

7. List all *refereed* publications either submitted or published during the *current* grant FY that acknowledge DOE ARM support. Two copies of all submitted papers should accompany the progress report. (Two reprints of all published papers should be submitted to the ARM Science Director when reprints are received. If this wasn't done at the time please include reprints with the progress report.*)

Lohmann, U., J. Feichter, C.C. Chuang, and J.E. Penner, 1999: Prediction of the number of cloud droplets in the ECHAM GCM, *J. Geophys. Res.*, 104, 9169-9198.

Lohmann, U., J. Feichter, J.E. Penner, and R. Leaitch, 2000: Indirect effect of sulfate and carbonaceous aerosols: A mechanistic treatment, *J. Geophys. Res*., 105. 12,193-12,206.

Penner, J.E., Chuang, C.C., and K. Grant, 1999: Climate Change and Radiative Forcing by Anthropogenic Aerosols: Research Findings During the Last 5 Years, La Jolla International School of Science, submitted, The Institute for Advanced Physics Studies, La Jolla, CA.

Chuang, C. C., J. E. Penner, K. E. Grant, Prospero, J. M., and G. H. Rau, 2000: Effects of anthropogenic aerosols on cloud susceptibility: A sensitivity study of radiative forcing to aerosol characteristics and global concentration. Submitted to *J. Geophys. Res.*

Nakajima, A. Higurashi , A., K. Kawamoto, and J. E. Penner, 2000: A possible correlation between satellite-derived cloud and aerosol microphysical parameters, submitted to *Nature*.

Rotstayn, L.D., B.F. Ryan, and J.E. Penner, 1999: Precipitation changes in a GCM resulting from the indirect effects of anthropogenic aerosols, *Geophys. Res. Lett*., submitted.

8. List all published (either paper or web-based) extended abstracts in the current FY that acknowledge DOE ARM support. Two copies of each should accompany the progress report*.

Chuang, C.C., J.E. Penner, and Y. Zhang, Simulations of aerosol indirect effect for IPCC emissions scenarios, *Proceedings of the 11th Symposium on Global Change Studies*, 9-14 January 2000, Long Beach, CA, American Meteorological Society, Boston, MA, p. 320-323, 2000.

Penner, J.E., and Y. Zhang, Projections of climate forcing by sulfate, organic aerosols, dust, and sea salt: Results from the IPCC model intercomparison workshop, *Proceedings of the 11th Symposium on Global Change Studies*, 9-14 January 2000, Long Beach, CA, American Meteorological Society, Boston, MA, p. 4 – 10, 2000.

9. Please update us on the status of submitted referred publications from the previous FY progress report. (If none, note "NONE"). The following were published:

Lohmann, U., J. Feichter, C.C. Chuang, and J.E. Penner, 1999: Prediction of the number of cloud droplets in the ECHAM GCM, *J. Geophys. Res.*, 104, 9169-9198.

Lohmann, U., J. Feichter, J.E. Penner, and R. Leaitch, 2000: Indirect effect of sulfate and carbonaceous aerosols: A mechanistic treatment, *J. Geophys. Res*., 105, 12,193-12,206.

Grant, K.E., C.C. Chuang, A.S. Grossman, and J.E. Penner, 1999: Modeling the spectral optical properties of ammonium sulfate and biomass burning aerosols; Parameterization of relative humidity effects and model results, *Atmos. Env.*, 33, 2603-2620.